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(11)

EP 1 001 474 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:
17.05.2000 Bulletin 2000/20

(51) Int. Cl.⁷: **H01L 41/04**, **H02N 2/06**,
H03F 3/30

(21) Application number: **98830684.1**

(22) Date of filing: **13.11.1998**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU
MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

• **Frattini, Giovanni**
27020 Travaco (IT)
• **Pedrazzini, Giorgio**
27100 Pavia (IT)
• **Ricotti, Giulio**
27043 Broni (IT)

(71) Applicant:
STMicroelectronics S.r.l.
20041 Agrate Brianza (Milano) (IT)

(74) Representative:
Pezzoli, Ennio et al
Jacobacci & Perani S.p.A.
Via Senato, 8
20121 Milano (IT)

(72) Inventors:
• **Fontanella, Luca**
30121 Venezia (IT)

(54) A driver circuit for controlling a piezoelectric actuator in charge mode

(57) A driver circuit (200) for controlling a piezoelectric actuator (Cpzt) in charge mode comprises an amplifier (OpAmp) having a first input terminal (INp), a second input terminal (INn), and a final stage (Mn, Mp) with an output terminal (OUT) for the connection of the actuator (Cpzt), the amplifier (OpAmp) having a further final stage (Mna, Mpa) with a further output terminal (OUTa) connected to the second input terminal (INn), the final stage (Mn, Mp) and the further final stage (Mna, Mpa) being connected in parallel with one another so that a current (Ipzt) which

passes through the output terminal (OUT) is proportional, in accordance with a predefined factor, to a current (Ia) which passes through the further output terminal (OUTa), the driver circuit (200) including capacitive means (Ca) with constant capacitance (Ca) connected to the second input terminal (INn) so that an electrical charge transferred to the actuator (Cpzt) is correlated with the control voltage (Vdac) in accordance with the predefined factor and the capacitance (Ca).

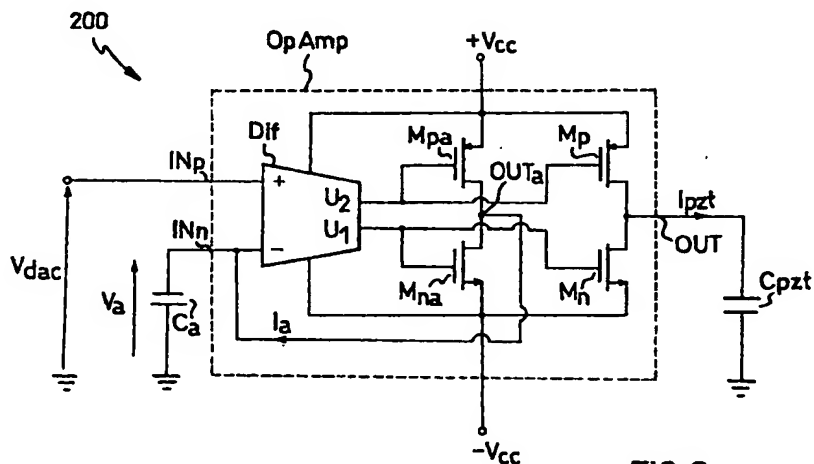


FIG.2

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Description

[0001] The present invention relates to a driver circuit for controlling a piezoelectric actuator in charge mode and, in particular, to a driver circuit according to the preamble of the first claim.

[0002] Piezoelectric actuators are used in various applications such as, for example, in disk-storage devices, for regulating a mechanical quantity in response to an electrical control quantity. A piezoelectric actuator is constituted by a chip enclosed between two metal plates; if the metal plates are charged electrically, the chip is deformed resiliently as if it were subjected to a mechanical stress. The deformation of the chip depends on the previous operation of the piezoelectric actuator as well as on the charge state of the metal plates.

[0003] The relationship between the electrical control quantity and the deformation is not therefore univocal so that a characteristic curve corresponding to this relationship has a hysteresis loop. The hysteresis loop of the characteristic curve of the piezoelectric actuator is greatly dependent on the type of control used (as well as on the frequency of the control quantity).

[0004] The electrical behaviour of the piezoelectric actuator may be represented, as a first approximation, by an equivalent circuit comprising a capacitor with variable capacitance (to which a dissipation resistor is connected in parallel during the generation of mechanical work). The piezoelectric actuator can therefore be driven by a voltage (voltage mode) or by a charge (charge mode).

[0005] A circuit for driving the piezoelectric actuator in voltage mode enables a voltage applied to the chip to be controlled by means of a control voltage. The driver circuit, which is constituted basically by an operational amplifier with voltage feedback, is extremely simple. However, this solution does not enable the deformation of the chip to be controlled precisely, because of the large hysteresis loop of the voltage/deformation characteristic curve of the piezoelectric actuator.

[0006] Greater accuracy can, however, be achieved by driving the piezoelectric actuator in charge mode since the hysteresis loop of the charge-deformation characteristic curve is generally much smaller than that of the voltage/deformation characteristic curve. A circuit for driving the piezoelectric actuator in charge mode enables a charge transferred to the chip to be controlled by means of the control voltage. The driver circuit requires an amplifier which measures a current passing through the chip by detecting a voltage at the terminals of a resistor connected in series with the chip; the amplifier produces, as an output, by means of an integration operation, a quantity indicative of the charge transferred to the chip over time. This quantity is transferred to the input of the drive circuit so as to interrupt its operation when the charge transferred to the chip reaches a desired value.

[0007] A disadvantage of the solution described above is that it requires a complex measuring amplifier (a sense amplifier). Moreover, in some applications such as, for example, when the piezoelectric actuator is disposed on a suspension arm of a disk-storage device, one plate of the piezoelectric actuator (constituted by the suspension arm) is connected to a reference terminal (or ground). The resistor used for measuring the current through the chip cannot therefore be connected to ground; this makes it necessary to use a differential sense amplifier which is extremely difficult to produce because of the high values of the input voltage (of the order of several tens of V).

[0008] The object of the present invention is to overcome the aforementioned drawbacks. To achieve this object, a driver circuit as described in the first claim is proposed.

[0009] In short, the present invention provides a driver circuit for controlling a piezoelectric actuator in charge mode, comprising an amplifier having a first input terminal for receiving a control voltage, a second input terminal, and a final stage with an output terminal for the connection of the actuator, the amplifier having a further final stage with a further output terminal connected to the second input terminal, the final stage and the further final stage being connected in parallel with one another so that a current which passes through the output terminal is proportional, in accordance with a predefined factor, to a current which passes through the further output terminal, the driver circuit including capacitive means with constant capacitance connected to the second input terminal so that an electrical charge transferred to the actuator is correlated with the control voltage in accordance with the predefined factor and the capacitance.

[0010] The present invention also proposes a disk-storage device comprising this driver circuit.

[0011] Further characteristics and the advantages of the driver circuit according to the present invention will become clear from the following description of a preferred embodiment thereof, provided by way of non-limiting example, with reference to the appended drawings, in which:

Figure 1 shows, schematically and in section, a hard-disk storage device in which the driver circuit of the present invention can be used,

Figure 2 shows an embodiment of the driver circuit.

[0012] With reference in particular to Figure 1, a hard-disk storage device 100 includes a sealed container 103, inside which there is a disk 105 constituted by a rigid circular support (with a diameter, for example, of between 7 and 10 cm) covered with a ferromagnetic material. The disk 105 is connected by means of a hub 107 to a shaft 110 connected to a suitable electric motor 115; the motor 115 keeps the disk 105 rotating about the shaft 110 at a constant frequency (for example, of

between 100 and 200 Hz).

[0013] The disk 105 is divided into tracks concentric with the rotation shaft 110, each track containing a plurality of cells each for storing one bit of data which is represented by different magnetization states of the ferromagnetic material; typically, the density of the data along a track is of the order of 120,000 BPI (bits per inch). The data is read from and written on the disk 105 by means of a head 120. The head 120 is generally constituted by an electromagnetic device which can detect or change the magnetization state of a cell disposed beneath it during a reading or writing operation, respectively.

[0014] The storage device 100 includes a suspension arm 125 coupled at one of its ends to a pin 126. The arm 125 terminates in a flexible suspension 127 on the free end of which a slider 129, which supports the head 120, is mounted. Typically, the slider 129 is fixed to the suspension 127 by a gimbal 130 which stiffens the structure with regard to rolling and pitching. The suspension 127 bends in order to exert a pressure which urges the slide 129 against an upper surface of the disk 105. The slide 129 floats on a cushion of air above the upper surface of the disk 105 when the disk 105 is in rotation, enabling the head 120 to follow the roughness of the disk 105 at an extremely small distance, for example, of the order of 10-30 nm.

[0015] A main actuator 135 and a secondary actuator 140 move the head 120 along a substantially radial axis relative to the disk 105 so as to position the head 120 over the desired track.

[0016] The main actuator 135 which, typically, is constituted by a voice-coil motor of the type used in loud speakers, pivots the suspension arm 125 about the pin 126, positioning the head 120 roughly (with a resolution of a few μm).

[0017] The secondary actuator 140 is constituted by two chips of piezoelectric material. The chips are made of ceramic material (for example an alloy based on lead, zirconium and titanium, or PZT), suitably polarized permanently in a manner such that its elemental crystals are oriented in a predominant direction; alternatively, quartz or piezoelectric crystal chips, or the like, are used. The chips of piezoelectric material 140 are fixed, perpendicular to the disk 105, to the sides of an easily deformable portion of the suspension 127; this deformable portion forms a hinge about which a tip of the suspension arm (a wrist) can pivot. When one chip of piezoelectric material lengthens and the other chip shortens, the deformable portion is bent slightly so that the wrist of the suspension arm consequently pivots about the hinge, positioning the head 120 finely and rapidly (with a resolution of the order of 0.1 μm); this allows disks with a very high track density, for example, of 25,000 TPI (tracks per inch) to be produced.

[0018] A control unit 145 puts the storage device 100 into communication with the exterior by means of a suitable connector 150. The control unit 145 is con-

nected to the main actuator 135 by means of a flexible cable 155 and to the head 120 and to the secondary actuator 140 by means of a further flexible cable 160. The control unit 145 processes an electrical signal supplied by the head 120 during a reading operation and sends suitable control signals to the head 120 during a writing operation. The control unit 145 also controls the main actuator 135 and the secondary actuator 140 in order to position the head 120 on the desired track.

[0019] Similar considerations apply to a storage device with several disks, with a floppy disk, with an optical disk, etc. The present invention may, in any case, also be used in other applications such as, for example, for controlling the positions of objects under a microscope, for controlling printing members of an ink-jet printer, etc.

[0020] With reference now to Figure 2, the control unit of the hard-disk storage device includes a driver circuit 200 for each chip of piezoelectric material, which is represented schematically by a capacitor (with variable capacitance) Cpzt; similar considerations apply if the circuit 200 simultaneously drives several chips or, in general, any other piezoelectric actuator.

[0021] The driver circuit 200 includes an operational amplifier OpAmp having an inverting input terminal INn, a non-inverting input terminal INp, and an output terminal OUT. The operational amplifier OpAmp has a differential input stage Dif having an inverting input terminal (-) and a non-inverting input terminal (+) which constitute the input terminal INn and the input terminal INp, respectively. The differential stage Dif also has two output terminals U1, U2 and two supply terminals; the supply terminals are connected to a positive supply terminal +Vcc (relative to a reference or ground terminal) and to a negative supply terminal -Vcc, respectively,

[0022] Connected in cascade with the differential stage Dif is a final power stage formed by two symmetrically complementary MOS field-effect transistors. In particular, the output terminals U1 and U2 of the differential stage Dif are connected to the base terminals of an n-channel MOS transistor Mn and of a p-channel MOS transistor Mp, respectively. The source terminal of the transistor Mn is connected to the negative supply terminal -Vcc, and the source terminal of the transistor Mp is connected to the positive supply terminal +Vcc. The drain terminals of the transistors Mn and Mp are connected to one another and define the output terminal OUT.

[0023] A control voltage Vdac (relative to ground), produced by converting a suitable digital control signal into analogue form, is applied to the non-inverting input terminal INp; the chip of piezoelectric material Cpzt is connected between the output terminal OUT and the ground terminal.

[0024] In the driver circuit 200 according to the present invention, there is an additional final stage similar to the main final stage Mp, Mn. In the embodiment

shown in the drawing, the output terminals U1 and U2 of the differential stage Dif are connected to the base terminal of an n-channel MOS transistor Mna and of a p-channel MOS transistor Mpa, respectively. The source terminal of the transistor Mna is connected to the negative supply terminal -Vcc and the source terminal of the transistor Mpa is connected to the positive supply terminal +Vcc. The drain terminals of the transistors Mna and Mpa are connected to one another to define an output terminal OUTa of the additional final stage Mna, Mpa, connected to the inverting input INn.

[0025] The main final stage Mn, Mp and the additional final stage Mna, Mpa, are connected in parallel with one another; a current Ipzt which passes through the output terminal OUT and which is supplied to the chip of piezoelectric material Cpzt is therefore proportional, in accordance with a predefined factor K (dependent on the physical structure of the transistors Mn, Mp and Mna, Mpa) to a current Ia which passes through the output terminal OUTa of the additional final stage Mna, Mpa, that is, $I_{pzt} = K \cdot I_a$.

[0026] The driver circuit 200 also includes a capacitor Ca (or other equivalent means) with constant capacitance. The capacitor Ca is connected between the inverting input terminal INn and the ground terminal.

[0027] In order to explain the operation of the driver circuit 200 described above, on the basis of the definition of current, it may be considered that the variation over time of an electrical charge Qpzt stored in the chip of piezoelectric material Cpzt is $dQ_{pzt} = I_{pzt} \cdot dt$; similarly, the variation over time of an electrical charge Qa stored in the capacitor Ca is $dQ_a = I_a \cdot dt = I_{pzt} \cdot dt / K = dQ_{pzt} / K$. Now, Ca indicates the capacitance of the capacitor identified by the same symbol in the drawing and Va indicates the voltage at the terminals thereof; on the basis of the definition of capacitance, $dQ_a = Ca \cdot dVa$, from which $dQ_{pzt} / K = Ca \cdot dVa$ and hence $dQ_{pzt} = K \cdot Ca \cdot dVa$.

[0028] It is assumed that a control voltage of value Vdac is applied to the non-inverting input terminal INp. The input terminals INn and INp are at the same potential (by the virtual ground principle), so that the voltage at the terminals of the capacitor Ca is brought (after a transitory phenomenon of negligible duration) from an initial zero value to an operating value equal to Vdac. By integrating the equation given above, it is found that the corresponding variation ΔQ_{pzt} of the electrical charge stored in the chip of piezoelectric material Cpzt is:

$$\Delta Q_{pzt} = (K \cdot Ca) \cdot V_{dac}$$

[0029] The electrical charge ΔQ_{pzt} transferred to the chip of piezoelectric material Cpzt is therefore directly proportional to the control voltage Vdac in accordance with the predefined factor K and the capacitance Ca.

[0030] Similar considerations apply if a different amplifier (preferably with a high gain and with a very

high input impedance) is used, if the main final stage Mn, Mp and the additional final stage Mna, Mpa are formed in another manner (possibly even differing from one another in structure), for example, with bipolar transistors, or with diodes for reducing cross-over distortion, or if the chip of piezoelectric material Cpzt and the capacitor Ca are not connected to ground, etc; in any case, the electrical charge ΔQ_{pzt} transferred to the chip of piezoelectric material Cpzt is correlated generically with the control voltage Vdac in accordance with the predefined factor K and the capacitance Ca.

[0031] These values are fixed, stable and easily determined; this enables the electrical charge actually transferred to the chip of piezoelectric material Cpzt, and hence the deformation thereof, to be controlled extremely accurately by means of the control voltage Vdac.

[0032] Moreover, the driver circuit of the present invention is relatively simple. This circuit does not in fact require a sense amplifier for actually detecting the current supplied to the chip of piezoelectric material Cpzt; on the contrary, the structure described above utilizes the negative feedback from the capacitor Ca and from the additional final stage Mna, Mpa, in order to set the desired current in the main final stage Mn, Mp directly.

[0033] In a preferred embodiment of the present invention, the predefined factor K is greater than 1 (for example, between 1 and 100). This reduces the power dissipated in the capacitor Ca and permits the use of a control voltage Vdac of a value substantially lower (for example a few V) than a voltage at the terminals of the chip of piezoelectric material Cpzt (for example, a few tens of V). The present invention may, however, also be implemented with any other value of the predefined factor K (even equal to or less than 1), for example, with the main and additional final stages identical to one another.

[0034] Naturally, in order to satisfy contingent and specific requirements, an expert in the art may apply to the above-described driver circuit many modifications and variations all of which, however, are included within the scope of protection of the invention as defined by the following claims.

Claims

1. A driver circuit (200) for controlling a piezoelectric actuator (Cpzt) in charge mode, comprising an amplifier (OpAmp) having a first input terminal (INp) for receiving a control voltage (Vdac), a second input terminal (INn), and a final stage (Mn, Mp) with an output terminal (OUT) for the connection of the actuator (Cpzt), characterized in that the amplifier (OpAmp) has a further final stage (Mna, Mpa) with a further output terminal (OUTa) connected to the second input terminal (INn), the final stage (Mn, Mp) and the further final stage

- (Mna, Mpa) being connected in parallel with one another so that a current (Ipzt) which passes through the output terminal (OUT) is proportional, in accordance with a predefined factor (K), to a current (Ia) which passes through the further output terminal (OUTa), the driver circuit (200) including capacitive means (Ca) with constant capacitance (Ca) connected to the second input terminal (INn) so that an electrical charge transferred to the actuator (Cpzt) is correlated with the control voltage (Vdac) in accordance with the predefined factor (K) and the capacitance (Ca).
2. A driver circuit (200) according to Claim 1, in which the predefined factor (K) is greater than 1.
 3. A driver circuit (200) according to Claim 2, in which the predefined factor (K) is between 1 and 100.
 4. A driver circuit (200) according to any one of Claims 1 to 3, in which the capacitive means (Ca) has a terminal connected to the second input terminal (INn) and a further terminal for connection to a reference terminal, the piezoelectric actuator (Cpzt) being connectible between the output terminal (OUT) and the reference terminal.
 5. A driver circuit (200) according to any one of Claims 1 to 4, in which the amplifier (OpAmp) is an operational amplifier, the first input terminal (INp) and the second input terminal (INn) being a non-inverting input terminal and an inverting input terminal, respectively.
 6. A driver circuit (200) according to any one of Claims 1 to 5, in which the final stage (Mn, Mp) and the further final stage (Mna, Mpa) have a symmetrically complementary structure.
 7. A driver circuit (200) according to Claim 6, in which the amplifier (OpAmp) includes a differential input stage (Dif) having a first input terminal (-) and a second input terminal (+) connected, respectively, to the first input terminal (INn) and to the second input terminal (INp) of the amplifier (OpAmp), a first output terminal (U1) and a second output terminal (U2), and a first supply terminal (-Vcc) and a second supply terminal (+Vcc), and in which the final stage (Mn, Mp) includes a first transistor (Mn) and second transistor (Mp) with opposite polarities and each having a first power terminal connected to the output terminal (OUT), and the further final stage (Mna, Mpa) includes a third transistor (Mna) and a fourth transistor (Mpa) having the same polarities as the first transistor (Mn) and as the second transistor (Mp), respectively, and each having a first power terminal connected to the further output terminal (OUTa), the first transistor (Mn) and the third transistor (Mna) having a second power terminal and a control terminal connected to the first supply terminal (-Vcc) and to the first output terminal (U1) of the differential stage (Dif), respectively, and the second transistor (Mp) and the fourth transistor (Mpa) having a second power terminal and a control terminal connected to the second supply terminal (+Vcc) and to the second output terminal (U2) of the differential stage (Dif), respectively.
 8. A driver circuit (200) according to Claim 7, in which the first transistor (Mn) and the third transistor (Mna) are constituted by n-channel MOS transistors and the second transistor (Mp) and the fourth transistor (Mpa) are constituted by p-channel MOS transistors, the first power terminal, the second power terminal, and the control terminal being a drain terminal, a source terminal and a gate terminal, respectively.
 9. A disk-storage device (100) comprising at least one suspension arm (125) for a head (120), a main actuator (135) for pivoting the suspension arm (125), and a piezoelectric actuator (140) for pivoting a free end of the suspension arm (125), characterized in that it includes the driver circuit (200) according to any one of Claims 1 to 8 for controlling the piezoelectric actuator (140) in charge mode.
 10. A disk-storage device (100) according to Claim 9, in which the storage device (100) is a magnetic hard disk.

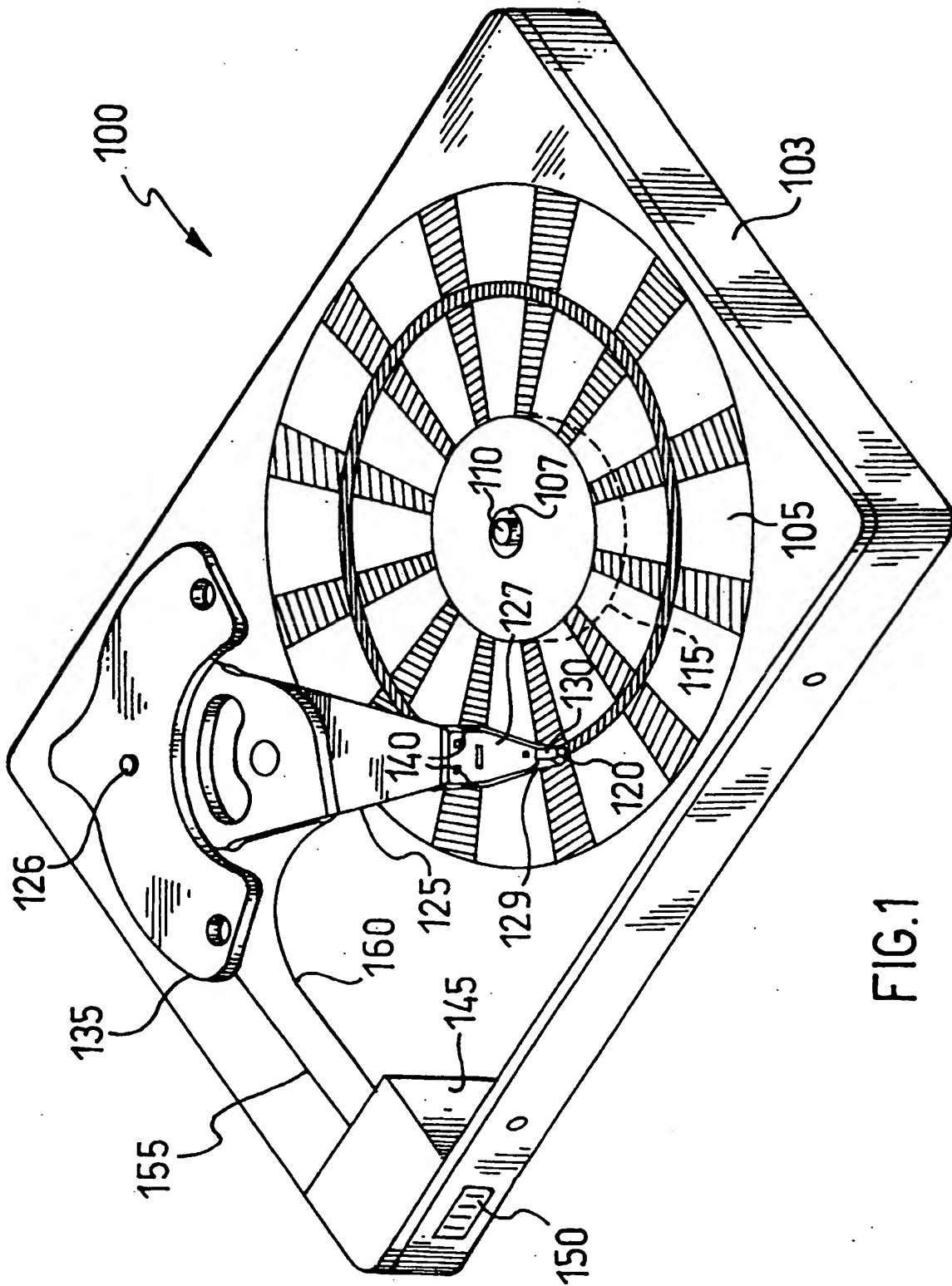


FIG. 1

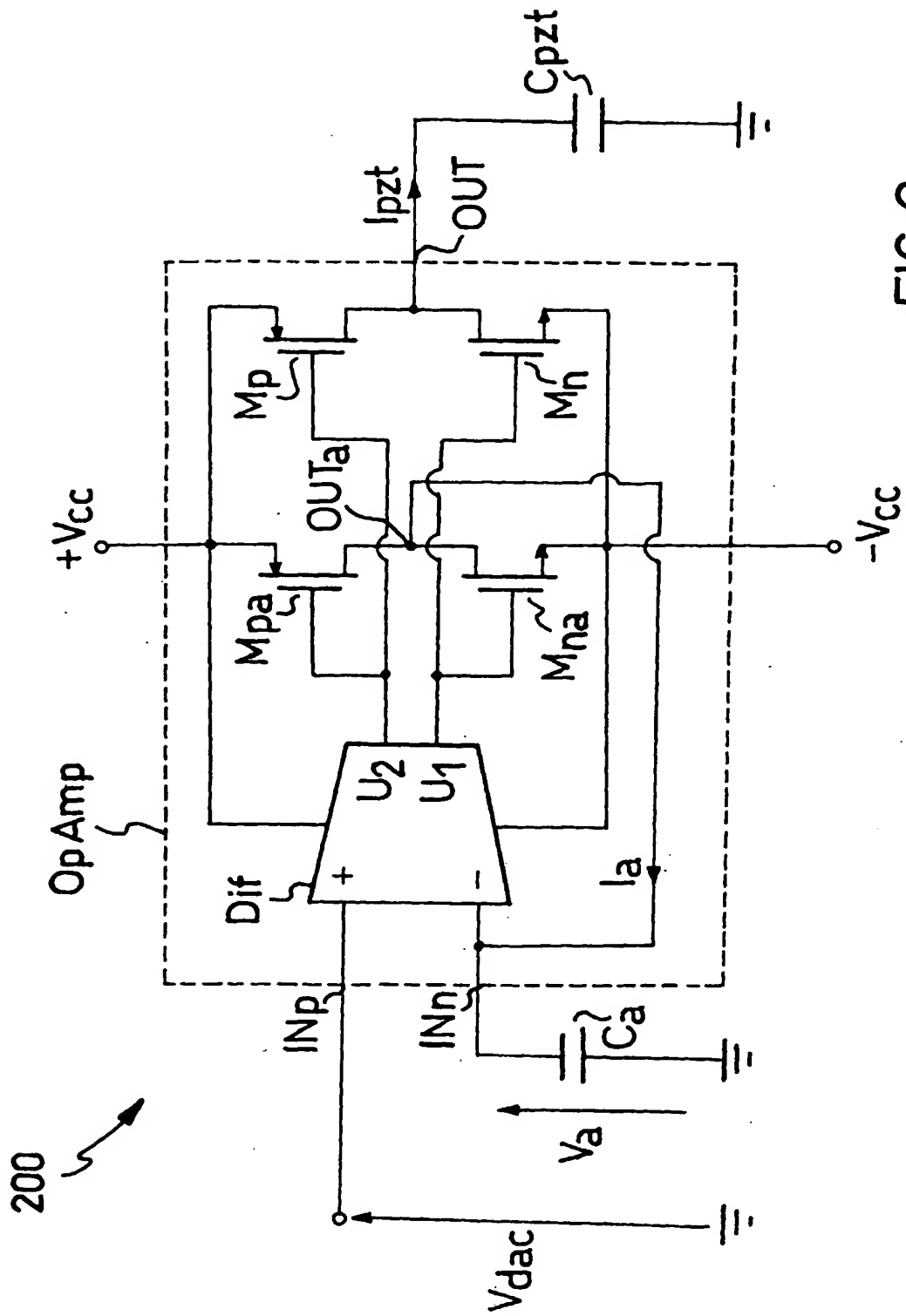


FIG.2



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EUROPEAN SEARCH REPORT

Application Number
EP 98 83 0684

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y	US 4 841 191 A (TAKADA KEIJI ET AL) 20 June 1989 * abstract; figure 10 * * column 2, line 11 - line 53 * * column 6, line 31 - line 47 *	1	H01L41/04 H02N2/06 H03F3/30
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Y	US 5 124 666 A (LIU SHEN-IUAN ET AL) 23 June 1992 * abstract; figure 3A * * column 2, line 5 - line 27 * * column 3, line 18 - line 36 *	1	
A	NEWCOMB C V ET AL: "Improving the linearity of piezoelectric ceramic actuators" ELECTRONICS LETTERS, 27 MAY 1982, UK, vol. 18, no. 11, pages 442-444, XP002099361 ISSN 0013-5194 * abstract; figures 1,2,4 * * page 442, column 2, line 1 - line 23 * * page 443, column 2, line 22 - line 47 *	1-10	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			H01L H02N H03F
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 9 April 1999	Examiner Visscher, E
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**ANNEX TO THE EUROPEAN SEARCH REPORT
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EP 98 83 0684

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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